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Environmental Impact Analysis to Achieve Sustainability for Artisan Chocolate Products Supply Chain

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Abstract: Small-scale artisan chocolate producers target environmentally conscious consumers and must work with their supply chain partners to measure and improve their environmental impacts. This research evaluates the environmental impact along the supply chain of artisan dark chocolate products in Indonesia and creates an action plan to reduce environmental impact. The Life Cycle Assessment (LCA) methodology was used. The analysis considers cocoa production from the farm level to the processing of cocoa beans into bars in three stages for 1 kg of dark chocolate: the farm maintenance and harvesting stage; post-harvesting stage; and processing stage. At the farm maintenance and harvesting stage, the significant contributions are 72.5% of total abiotic depletion (AD), 47.2% of total global warming (GW), 80.2% of total eutrophication (EU). The significant contributions at the post-harvesting are 31.2% of total AD, 51.8% of total GW, 83% of total EU, 26.4% of total ozone layer depletion (ODP), 20.1% of total cumulative energy demand (CED) and non-renewable fossil (NRF), and 36.9% of total CED renewable biomass (RB). And at the processing stage, the significant contributions are 20.5% of total AD, 15% of total GW, 4% of total ODP, 13.1% of total acidification (AC), 12% of total EU, 10% of total fossil resource scarcity (FRS), and 1.6% of total CED NRF. Changes to the farm maintenance and harvesting stages contributed the most to environmental impact reduction by improving waste utilization and the treatment and selection of environmentally friendly materials.

Keywords: artisan chocolate; cocoa; environmental impact; life cycle assessment (LCA); supply chain

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1. Introduction

The cocoa industry is the economic backbone of many countries around the world and encompasses all businesses associated with chocolate production, from the supply and processing of raw materials to the selling of chocolate to consumers [1]. More than 6 million producers participate in the cocoa industry and around 50 million people depend on the cocoa trade [2,3]. The cocoa industry is not always environmentally friendly; the maintenance, harvesting, and processing of cocoa beans into chocolate generates greenhouse gas emissions as part of the agri-food industry, which accounts for more than 25% of global greenhouse gas emissions [4,5]. For example, the unrestrained use of chemical fertilizers to increase cocoa bean production degrades the environment. Globally, 95% of cocoa beans are used for bulk or commodity cocoa, with only 5% used for specialty cocoa [6,7].

Artisan chocolate is defined as a craft, due to the process of producing and transforming cocoa beans into bars [8,9]. The intimate knowledge and understanding possessed by small chocolate makers (i.e., artisans) allows for the creation of a superior product [6,8,10]. In circumstances where artisans do not exist in a company, the chocolate cannot be called

artisanal [11]. Artisan and craft food production typically describes authentic craftsmanship made in small batches for local markets, although large organizations tend to use the term "craft" during marketing [9,10].

Artisan or craft chocolate is considered premium branding by selling differences and innovations through delicate taste, local sourcing, environmentally responsible production, and socially inclusive attributes, which is referred to as a "brand community" [8]. With the high price tag of crafted premium products, artisan chocolate needs to have delicate flavors, uniqueness, and diversity using, for example, specialty cacao beans [11,12]. To accomplish this, the materials need to be directly sourced from the supply chain to ensure quality [9,13]. Specialty cacao characteristics include quality, genetics, origin, certification, and direct trade [6,14]. Moreover, moving up the supply chain creates opportunities for other brands to confirm and certify that their products are manufactured in close collaboration with both local and indigenous farmers. It enables them to easily influence and monitor the environmental impacts of the supply chain, not just the production process.

The artisan (or craft) chocolate market has seen a doubling in cocoa commodities for more than two decades, and this growth has the potential to promote an ethical, environmentally friendly, sustainable chocolate industry [7]. Specialty cocoa utilizes direct trade, with cocoa bean prices that exceed those of commodity cocoa due to the principles of transparency, accountability, and responsible pricing that contributes to improvements in farmer living conditions and decreases the environmental impact of cocoa production [1]. The importance of this social aspect is due to the fact that the majority of cocoa farmers live below the poverty line and lack access to income-enhancing opportunities [9]. The position of artisanal chocolate and specialty cocoa in the chocolate industry could lead to a more sustainable and socially responsible chocolate industry with higher margins and closer connections to farmers in the future [6].

More than 70% of the world's artisan cocoa market is dominated by the United States and European nations, with Germany and Belgium being the lead consumers of artisan chocolate [9,15,16]. In the United States, artisan cocoa industries play an essential role by increasing the added value in the U.S. chocolate market [8,9,17]. These companies usually focus on premium products that target a particular set of consumers who question the origin of raw materials and production methods in regard to environmental sustainability [4]. Ecuador, Venezuela, Peru, and the Dominican Republic are among the Latin American nations supplying the chocolate industry and use specialty cocoa beans as their primary raw material [10]. Indonesia's contribution to the global artisan chocolate market is 0.06% for artisan chocolate producers and 2.02% for specialty cocoa bean producers [9].

The artisan cocoa industry in Indonesia is in the beginning stages of development and targets a niche market at a premium price. This is why the Indonesian government has begun to focus on the development of the cocoa industry by enacting regulations that support the growth of the small-scale cocoa industry and the development of specialty cocoa in national and global markets [18]. For the domestic market, The Indonesian government has increased the market share target of the artisan chocolate industry from 2% to 10% of domestic chocolate consumption [19]. For the global market, Indonesian products have been already known to have a diverse flavor based on the environmental characteristics such as soil type, rainfall, and altitude that are different from each region [20–22]. The product has been exported to several European, American, and Asian nations [23]. This has created an opportunity for small-scale artisanal companies in several regions of Indonesia that collaborate with local cocoa producers. Several artisanal chocolate producers in Indonesia are dedicated to nurturing farmers, developing local processing companies, and succeeding in the global market with sustainable practices.

The commodity cocoa supply chain is lengthy and characterized by several actors, including farmers, traders, processors, manufacturers, retailers, and consumers (Figure 1a) [24,25]. The supply chain in Indonesia involves many actors on the traders' side, including local collectors at the village and district levels and foreign and domestic buyers [26]. Cocoa farmers do not conduct transactions with the manufacturers directly. In contrast, the artisanal chocolate supply chain is short, because traders are not involved, and the chocolate artisan company handles the grinding process (Figure 1b). Many chocolates artisan company take pride in sourcing materials that improve farmers' living standards or address environmental impacts [9]. Producers also often prefer to obtain cacao products directly from the farm or local intermediaries, thus benefiting from consistent quality control [6,13].

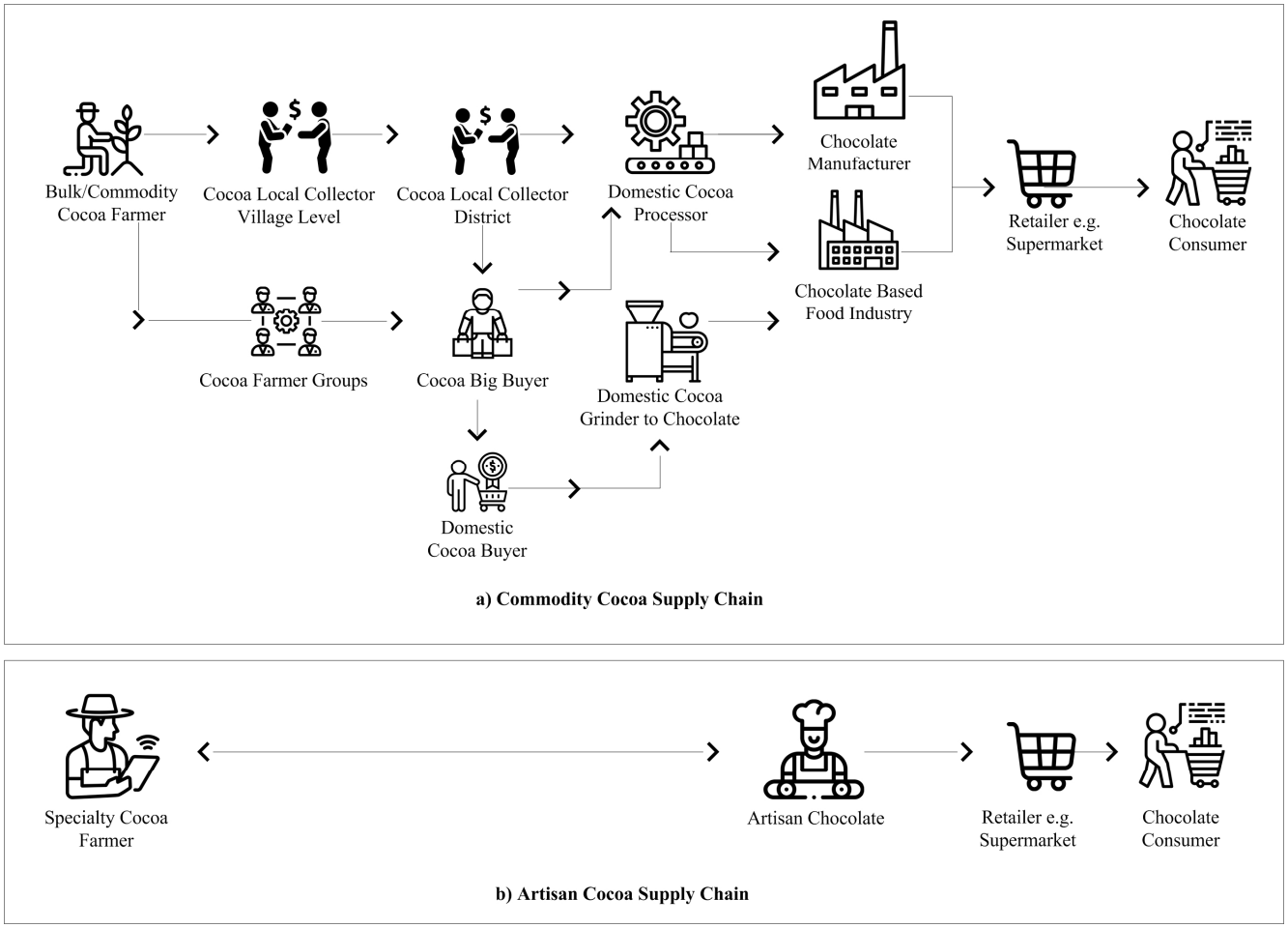


Figure 1. Comparing The Supply Chains of Commodity Cocoa (**a**) and Artisanal Cocoa (**b**).

Consequently, transparent, and sustainable actions are required to identify production processes that require improvement, especially in regard to emissions along the supply chain, which has multiple indicators (e.g., global warming, eutrophication, and acidification). Such environmental impacts have to be observed from the broader supply chain context. Thus, the artisan industries must start measuring their environmental impacts as a sustainability factor.

Life-cycle assessment (LCA) can be used to measure environmental impact [10,11]. The LCA method evaluates the environmental sustainability of production systems and can provide holistic system solutions [27]. LCA tools are used to identify and quantify several of the main factors causing environmental impacts during the cocoa production process [28]. It can also compare the environmental effects of companies in the same sector, analyze the effects of changes, and avoid shifting impacts from one phase to another [14,15].

Other benefits include the identification of significant process that need improvements and monitoring the future progress of the industry in terms of helping consumers make informed choices toward the sustainable consumption of chocolate products [3,16].

Most preliminary LCA studies focus on the manufacturing aspects of the supply chain [5,29,30], with no studies focused on the integrated supply and distributive chain of the artisan cocoa industries. This whole chain perspective is essential due to this sector's unique characteristics, including its segmented customer profile, low volume, despite its high-margin products, environmentally conscious branding, cordial relations with farmers, and shorter supply chain. Therefore, this study offers an additional perspective with a more in-depth analysis of the artisan chocolate industry and its supply chain's environmental impacts using LCA. Studies on the environmental impact of cocoa in Indonesia are still limited. One study conducted by Utomo et al. [31] spans almost a decade but is limited to measuring only farmer chains. This present LCA measurement study will be the first to calculate the environmental impact on two chains, namely the farmer chain and the cocoa production chain in the cocoa artisan industry sector. A LCA is a critical step to help cocoa farmers and artisans identify the sources of significant environmental impact in the artisan chocolate supply chain, especially given the limited number of environmental assessments performed thus far in this sector of the chocolate industry. Therefore, this paper contributes to helping policymakers and relevant stakeholders identify which stages of the supply chain can be improved to maintain and increase sustainability, which is of particular interest to the environmentally conscious consumers that this industry targets.

The remainder of this paper is organized as follows. Section two presents the materials and methods of the research. Section three presents the results, and section four discusses the results. Finally, section five provides the conclusions of the research.

2. Materials and Methods

This study employs the LCA methodology following ISO 14040-44:2006 [5,32,33] that consists of four stages: goal and scope definition; life-cycle inventory; impact assessment; and interpretation of results [32,34]. Upon completion, possible actions that could reduce environmental impact were identified and simulated. The base calculation and proposed improvements were then compared to increase the sustainability of the artisan cocoa industry. This LCA study uses the cradle-to-gate approach and the functional unit (FU) analyzed was 1 kg of dark chocolate, including packaging.

2.1. Study Site

A small-scale, artisan chocolate company called Macoa (Mandar Cocoa), located in the Polewali Mandar Regency in West Sulawesi Province, Indonesia, was chosen for this study, because the company has experience building an artisanal chocolate industry, especially on the island of Sulawesi. Sulawesi Island contributes more than 60% of the commodity cocoa production [35–37]. The farmers partnered with Macoa are located in the Luyo District and have more than two decades of experience managing cocoa plantations. Macoa and the farmers have been working together to supply cocoa beans for the past seven years. The distance between the cocoa plantations (3°24′28.80″ S, 119°9′21.60″ E) and the artisanal industries (3°24′43.20″ S, 119°14′45.60″ E) is 10 km (Figure 2).

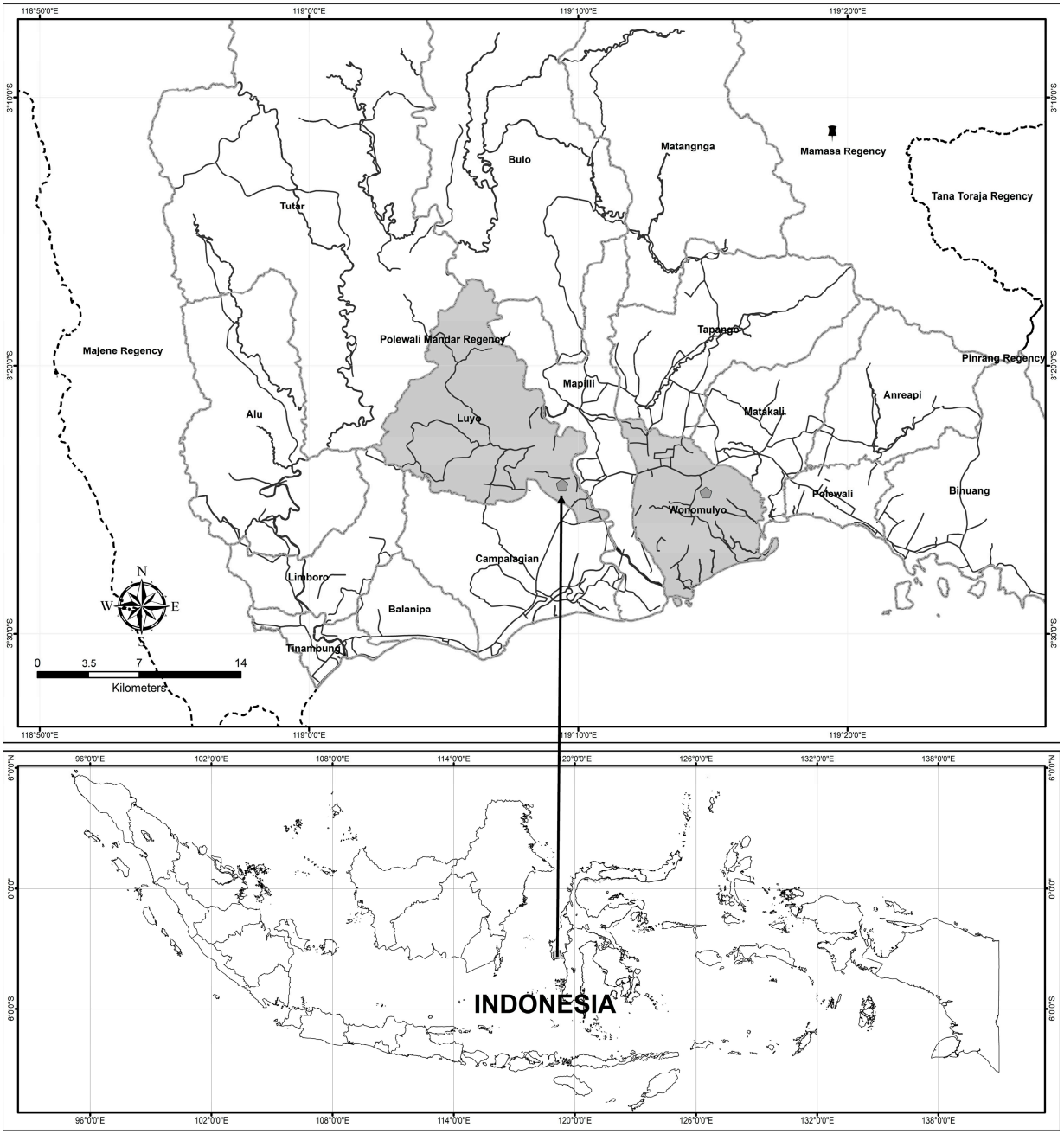


Figure 2. Cocoa Plantation and Artisan Chocolate Site Map in Indonesia, the grey area shows the regencies where the data is collected.

2.2. System Boundaries

The system boundaries consisted of the farm maintenance stage, the post-harvesting stage, and the processing stage. The farm maintenance stage includes plant maintenance and harvesting activities. The post-harvesting stage consists of the fermentation, drying, and transportation of the cocoa beans. The processing stage consists of the roasting, winnowing, grinding, pressing, mixing, tempering, molding, and packaging of the cocoa beans into chocolate. This study did not assess the life cycles involved in producing fertilizer, sugar raw materials, vanilla, or packaging materials. It also did not include the planting process, retail processes, or end-of-life stages. Figure 3 illustrates the system boundaries used in this study.

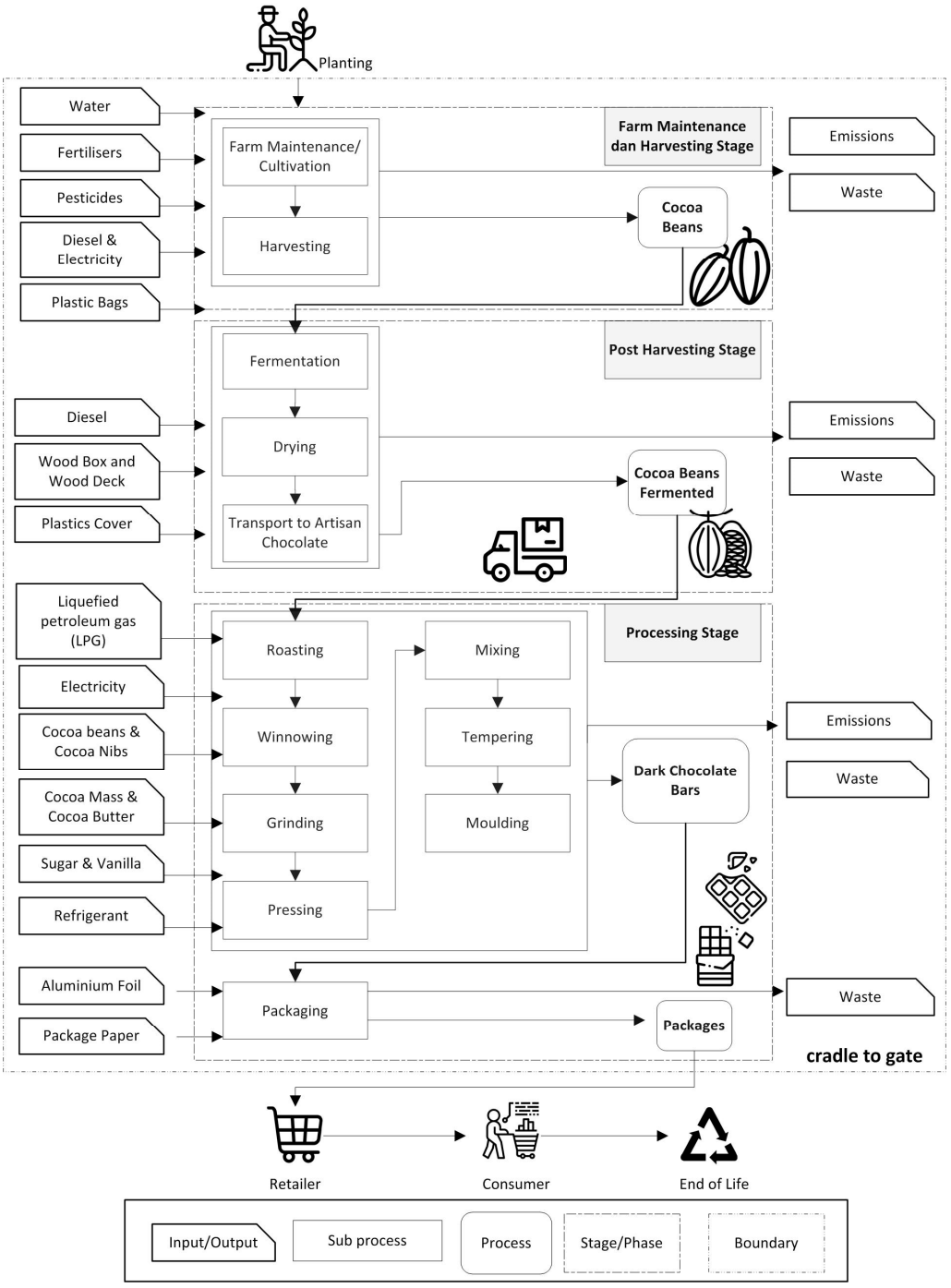


Figure 3. Mapping Process and Boundary System.

2.3. Impact Assessment Indicators

Since this study focuses on the agri-food industry, the recommended indicators limit the environmental impact in accordance with an environmental product declaration [3,21]. Its measurement involves the use of the CML IA baseline method, which is an indicator of abiotic depletion (AD), global warming (GW), ozone layer depletion (ODP), acidification (AC), and eutrophication (EU). The cumulative energy demand (CED) method was used to calculate energy consumption on total non-renewable fossil (NRF) and renewable biomass (RB), while fossil resource scarcity (FSR), land use (LU), and water consumption (WC) were measured with the ReCiPe 2016 midpoint H method [38].

2.4. Life-Cycle Inventory

Inventory data for the artisanal chocolate production process (e.g., raw materials, chemical and energy use, by-products, emissions, and waste) were collected from various sources. Primary data were sourced from observations and interviews with cocoa farmers directly on plantations and chocolate artisan companies in 2020–2021. Secondary data were obtained from the relevant literature and databases (i.e., Ecoinvent v3.0) and Agri-footprint 5.0 [5,30,38,39]. Ecoinvent is a database providing a wide range of environmental parameters of materials, processes, and products, such as energy consumption, greenhouse gas emissions, water use and environmental emissions and impacts. It is a continually updated and maintained by the Ecoinvent Association, which is a nonprofit organization based in Switzerland. It is a valuable source for the Life Cycle Inventory (LCI) and widely accepted to be used in LCA. Agri-footprint is also another database used in LCA that is more focused on the agriculture and food sector developed and maintained by Blonk Agri-footprint BV [40]. All of these databases were accessed through the SimaPro 9.4.0.3 faculty version modeling software that were used to conduct the LCA modeling [41]. The limitation of material selection based on Indonesia's geographical location when inputting data into the SimaPro software makes it possible to select Global (GLO) and Rest of World (RoW) geography. However, using these database, the results can not be precise, but sufficient in this case [42].

2.4.1. Farm Maintenance and Harvesting Stage

The farm maintenance and harvesting stage includes the provision of water for cocoa plants. The water is obtained from the river and pumped using an electric or diesel-powered machine that has an energy requirement of 0.0092 kWh. The plants require 4.09 kg or 4 L water per kg of dark chocolate. The fertilizer requirement (a combination chemical and organic fertilizer) was 0.0538 kg. At this stage, the emission output in water includes urea and NPK fertilizers in the form of nitrates and phosphates. Waste from leaf and twig pruning of the cocoa plants was 0.230 kg per kg dark chocolate. Cacao husk pod waste was 0.38 kg per kg dark chocolate. The input and output data for this stage are summarized in Table 1.

Table 1. Input and Output Data for the Farm Maintenance and Harvesting Stage.

Input/Output	Unit/FU	Amount	Source	Data Type
Land Use	ha	0.000955	Cocoa producer	Primary
Water	kg	4.0944882	Cocoa producer	Primary
Fertilizer				
Urea	kg	0.0113846	Utomo et al. [31]	Secondary
SP36	kg	0.0006923	Utomo et al. [31]	Secondary
Organic Fertilizer	kg	0.0035846	Utomo et al. [31]	Secondary
Pesticides				
Insecticide	kg	0.0007269	Ecoinvent v3.0	Secondary
Energy				
Electricity	kWh	0.0138462	Cocoa producer	Primary
Diesel	kWh	0.0092308	Cocoa producer	Primary
Others				
Polypropylene	kg	0.0009231	Cocoa producer	Primary
Water Emission				
Nitrates	kg	1.238×10^{-11}	Utomo et al. [31]	Secondary
Phosphates	kg	6.992×10^{-12}	Utomo et al. [31]	Secondary
Chemical oxygen demand	kg	1.231×10^{-19}	Utomo et al. [31]	Secondary
Soil Emission				
Pesticides	kg	0.0007269	Ecoinvent v3.0	Secondary
Waste				
Biowaste, open dump	kg	0.2307692	Cocoa producer	Primary
Final Waste Flow				
Waste Organic	kg	0.3846154	Cocoa producer	Primary

The Functional Unit (FU) analyzed is 1 kg of dark chocolate.

2.4.2. Post-Harvesting Stage

This stage includes the provision of supporting materials for the fermentation, drying, and transport needed to process dry cocoa beans to artisanal chocolate. The fermentation box consists of sawn wood (0.00016 cm^3 per kg dark chocolate). Wood is also needed to dry the cocoa beans (0.00052 cm^3 per kg dark chocolate). Polypropylene is used as a plastic cover during the drying process. Air emissions created during the fermentation process includes acetic acid (0.34 kg per kg dark chocolate), lactic acid (0.01 kg/FU), and chemical oxygen demand (COD; 0.07 kg/FU). Pulp liquid waste is also produced during fermentation (0.25 kg/FU). The input and output data are provided in Table 2.

Table 2. Input and Output Data for the Fermentation and Harvesting Stage.

Input/Output	Unit/FU	Amount	Source	Data Type
Wood Fermentation Box	cm^3	0.00016	Cocoa producer	Primary
Wood Drying Tools	cm^3	0.000522	Cocoa producer	Primary
Others				
Polypropylene (drying cover)	kg	0.002	Ecoinvent v3.0	Secondary
Emissions to Air				
Acetic acid	kg	0.34	Cocoa producer	Primary
Lactic acid	kg	0.01	Cocoa producer	Primary
Chemical oxygen demand	kg	0.07	Cocoa producer	Primary
Waste				
Polypropylene (plastic bag)	kg	0.0012	Ecoinvent v3.0	Secondary
Polypropylene (drying cover)	kg	0.002	Ecoinvent v3.0	Secondary
Biowaste (fermentation)	kg	0.25	Ecoinvent v3.0	Secondary

The Functional Unit (FU) analyzed is 1 kg of dark chocolate.

2.4.3. Processing Stage

There are eight steps involved in chocolate production from roasting to packaging (Figure 2). Processing 1 kg of dark chocolate product with a concentration of 80% chocolate requires several raw materials and energy. The raw materials are 0.708 kg of cocoa mass, 0.176 kg of cocoa butter, 0.11 kg of sugar, and 0.0002 kg of vanilla. The raw materials are mixed into the mixing machine with an energy requirement of 0.103 kWh. Creating a certain mass of cocoa requires a roasting process with an energy requirement of 0.09 kg of liquid gas fuel, a winnowing process by separating the cocoa beans from the cocoa bean shell membrane, and the process of grinding the cocoa beans with an energy requirement of 0.09 kWh. The cocoa mass is processed into a pressing machine to produce cocoa butter with an energy requirement of 0.006 kWh. Mass cocoa is processed in a tempering machine with an energy requirement of 0.136 kWh to produce a quality chocolate final product. This process is the most critical stage in the manufacture of chocolate because it allows the formation of crystals in the chocolate mixture. The input and output data are illustrated in Table 3.

A molding machine (0.01 kWh per kg dark chocolate) is used to print dark chocolate into molds. Clean water is used to rinse the machine tool containers at an average of 0.4–0.5 kg of water per kg dark chocolate. Refrigeration for the chocolate dough cooling process uses tetrafluoromethane to ensure quick cooling. Also known as Gas R-134a, tetrafluoromethane is a mixed refrigerant gas that replaces freon R22. The cooled chocolate is removed from the mold, then packaged with aluminum oxide (0.019 kg) and printed paper (0.04 kg).

Table 3. Input and Output Data in Chocolate Processing.

Input/Output	Process	Unit/FU	Amount	Source	Data Type
Energy					
Liquified Petroleum Gas (LPG)	Roasting	kg	0.0986301	Chocolate producer	Primary
Electricity, medium voltage	Winnowing	kWh	0.0060274	Chocolate producer	Primary
Electricity, medium voltage	Grinding	kWh	0.0912329	Chocolate producer	Primary
Electricity, medium voltage	Pressing Liquor	kWh	0.0663014	Chocolate producer	Primary
Electricity, medium voltage	Mixing	kWh	0.1031507	Chocolate producer	Primary
Electricity, medium voltage	Tempering	kWh	0.1369863	Chocolate producer	Primary
Electricity, medium voltage	Molding	kWh	0.0125068	Chocolate producer	Primary
Ingredients					
Sugar, from sugar cane	Mixing	kg	0.1154795	Agri-footprint 5.0	Secondary
Vanilla	Mixing	kg	0.0002740	Chocolate producer	Primary
Cocoa Butter	Pressing	kg	0.1767123	Chocolate producer	Primary
Cocoa Mass	Grinding	kg	0.7082192	Chocolate producer	Primary
Water					
Water (tap water)	Grinding	kg	0.4424658	Chocolate producer	Primary
Water (tap water)	Pressing Liquor	kg	0.4424658	Chocolate producer	Primary
Water (tap water)	Mixing	kg	0.5	Chocolate producer	Primary
Water (tap water)	Tempering	kg	0.5	Chocolate producer	Primary
Others					
Tetrafluoroethene	Molding	kg	0.0031096	National Refrigerants Inc. [43]	Secondary
Printed paper	Packaging	kg	0.04	Chocolate producer	Primary
Aluminum oxide	Packaging	kg	0.0190411	Ecoinvent v3.0	Secondary
Emission to air					
CO_2	Roasting	kg	0.0029452	Chocolate producer	Primary
Methane	Roasting	kg	2.329×10^{-7}	Chocolate producer	Primary
Dinitrogen monoxide	Roasting	kg	4.671×10^{-9}	Chocolate producer	Primary
Hydrogen Fluoride	Roasting	kg	7×10^{-9}	Chocolate producer	Primary
Emission to water					
Water	Grinding	l	0.4424658	Chocolate producer	Primary
Water	Pressing Liquor	l	0.4424658	Chocolate producer	Primary
Water	Mixing	l	0.5	Chocolate producer	Primary
Water	Tempering	l	0.5	Chocolate producer	Primary
Municipal solid waste	Winnowing	kg	0.0465753	Chocolate producer	Primary
Municipal solid waste	Packaging	kg	0.005	Chocolate producer	Primary

The Functional Unit (FU) analyzed is 1 kg of dark chocolate.

3. Results

3.1. Life Cycle Impact (LCI) Assessment Overall Process

The contribution of the three main stages to the total impact of the process can be seen in Figure 4. The total impact (1) AD (1.28×10^{-5} kg Sb eq), (2) GW (1.44 kg CO_2 eq), (3) ODP (1.2×10^{-7} kg CFC-11 eq), (4) AC (5.2×10^{-3} Kg SO_2 eq), (5) EU (6.7×10^{-3} kg PO4---eq), (6) CED total non-renewable fossil (NRF) and renewable biomass (RB) (34.65 MJ), (7) LU (19.04 m2a crop eq), (8) FRS (3.6×10^{-1} kg oil eq), and (9) WC (1.1×10^{-1} m^3). The farm maintenance and harvesting stage contributed most to LU at 95.5%, AD at 36%, EU at 25.1%, and GW at 24.7%, which were mainly related to the LU needed for cocoa cultivation and maintenance, the use of phosphate fertilizers, and cocoa husk pod biowaste. The post-harvesting stage had its highest contributions to CED at 51%, GW at 22.2%, EU at 20.6%, and AD at 20%, which were related to the use of urea fertilizer, fermented biowaste, and the use of sawn wood materials. The processing stage contributed highly to water consumption (WC) at 97.5%, FRS at 78.6%, ODP at 77.7%, AC at 76%, EU at 54.3%, GW at 53.2%, and AD at 43.8%, mainly due to the need for water in sugar cane, the use of LPG fuel, and the consumption of electricity.

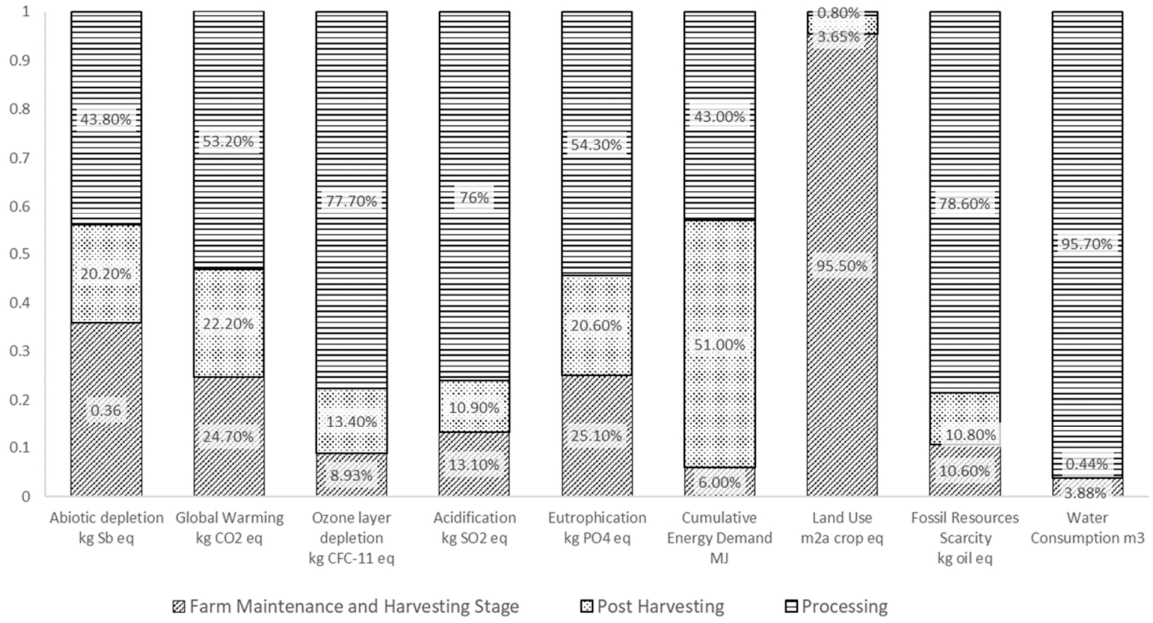


Figure 4. Processes contribution (in %) to the environmental impact of the dark chocolate considering its life cycle.

The processes contributing to impacts at each cocoa supply chain stage are described in the next section. The percentage contribution to each LCA impact category is shown in Figure A1 in Appendix A for each stage (farm maintenance and harvesting, post-harvesting stage, and processing).

3.2. Farm Maintenance and Harvesting Stage

Farm maintenance and harvesting are essential for cocoa bean production. Quality cocoa beans are one of the most critical factors in ensuring that the dark chocolate produced meets market standards [6]. The use of phosphate fertilizers contributes 26% of AD at a value of 3.4×10^{-6} kg Sb eq. In comparison, urea fertilizer only contributes 8.9% to the impact. Cocoa pod husk, as the waste from harvesting activities that are thrown away on the land around the cocoa trees, has an impact of 0.00144 kg PO4 eq (21%) on EU, 0.244 kg CO_2 eq (17%) on GW, and 0.00102 m2a crop eq on LU.

3.3. Post-Harvesting Stage

The post-harvesting stage includes the process of fermenting and drying the cocoa beans to reach a maximum moisture content of 7.5% [44]. It also includes the transportation of fermented dry cocoa beans to the chocolate processing location. Sawn wood material for the fermentation box and cocoa bean drying boards impacted 15.7 M eq (94%) on the CED of RB (biomass, wind, solar, geothermal, and water). In contrast, the impact on CED from NRF (fossil, nuclear, biomass) also comes from sawn wood material with a contribution of 1.25 MJ eq (11%). Pod husk cacao waste impacted 0.203 kg CO_2 eq (14%) on GW. The impact on GW from the use of sawn wood material for the fermentation box and drying boards had an impact of <10% (0.0851 kg CO_2 eq). Cocoa bean transportation activities using light commercial vehicles had an impact value of 0.0162 kg CO_2 eq. Pod husk cacao also impacted the EU's 0.0012 kg PO4 eq (18%). Sawn wood material for drying cocoa beans had an impact of 1.9×10^{-6} kg Sb (56.2%) on AD and 1.27×10^{-8} kg CFC-11 eq (10.1%) on ODP.

3.4. Processing Stage

The processing stage includes all processing machines and packaging activities. Sugar cane and sugar cane seed for the provision of sugar raw materials in the mixing process

and tap water for the cleaning of the processing machine equipment containers had an impacted 0.11 m^3 eq (95.7%) on WC. The highest contribution on sugar cane at farms was WC with a value of 0.0994 m^3 eq, whereas in tap water, it was only 0.00179 m^3 eq. The impact on FRS comes from the consumption of gas fuel using liquefied natural gas (LPG) in the roasting process of cocoa beans, which impacted 0.119 kg of oil eq (40%). The use of electrical energy in four chocolate processing machines among the other machines for grinding, pressing, mixing, and tempering the chocolate had an impact of 40%, with a value of 0.109 kg oil eq. At the same time, printed paper used for packaging was worth 0.0289 kg oil eq.

The impact on ODP from using LPG fuel in the cocoa bean roasting process contributed 52% with a value of 6.6×10^{-8} kg CFC-11 eq. The use of electrical energy in chocolate processing machines impacted 1.3×10^{-8} kg CFC-11 eq (10%) on ODP. The impact on AC was from using electrical energy to operate the machines at 34.9%, with a value of 0.00183 kg SO_2 eq. The use of LPG fuel in the roasting process had an impact of 11.2%, with a value of 0.000585 kg SO_2 eq. Printed paper and aluminum oxide as packaging materials contributed around 16%, with a 0.0008 kg SO_2 eq. The impact on the EU generated from using electrical energy to operate the processing machines had an impact of 34.8%, with 0.0022 kg PO4 eq. Another impact source on EU was the sugar cane used at the farms at an impact of 12.7%, with a value of 0.0008 kg PO4 eq Agri-footprint-mass allocation.

The impact of GW, 0.424 kg CO_2 eq (31.2% of the impact) is attributed to the electricity consumption in the processing stage. The printed paper also contributed 0.103 kg CO_2 eq to the GW impact indicator. In addition, AD during the processing stage also contributed due to the use of printed paper for dark chocolate packaging materials at an impact of 17.3% with a value of 0.00000221 kg Sb eq. The impact contribution to AD from refrigeration with the replacement for freon (tetrafluoroethane), in the molding process had the same percentage and value results. The impact on CED and NRF was 17 MJ. The most enormous impact value came from the use of LPG at 32% with a value of 5.45 MJ and from the use of electrical energy with a value of 4.93 MJ.

Table 4 provides an overview of contributions of the processes in each stage for each environmental indicator. This research set the minimum significant impact value at a value of >10%. This minimum percentage value is considered sufficient to contribute to the overall impact based on the results of direct interviews with farmers and industry practitioners and refers to sources of the impact in related studies [3,13,22] that were performed LCA on cocoa and chocolate. The significant impact values are symbolized by a filled circle (●), and insignificant impact values are symbolized by an unfilled circle (○). The processes that have significant impact values are named as significant process.

Table 4. Environmental Indicator Matrix and Cocoa Artisan Supply Chain Stages.

	Environmental Indicators								
Chain Stage	**AD**	**GW**	**ODP**	**AC**	**EU**	**CED**	**FRS**	**LU**	**WC**
Stage 1. Farm Maintenance	36%	24.7%	8.93%	13.1%	25.1%	6.0%	10.6%	96.0%	3.90%
Farm Maintenance	●	○	○	○	○	○	○	●	○
Harvesting	○	●	○	○	●	○	○	○	○
Stage 2. Post-harvesting	20.2%	22.2%	13.4%	10.9%	20.6%	51.0%	10.8%	3.70%	0.45%
Fermentation	○	●	○	○	●	○	○	○	○
Drying	●	○	●	○	○	●	○	○	○
Transportation	○	○	○	○	○	○	○	○	○

Table 4. *Cont.*

	Environmental Indicators								
Chain Stage	**AD**	**GW**	**ODP**	**AC**	**EU**	**CED**	**FRS**	**LU**	**WC**
Stage 3. Processing	43.8%	53.2%	77.7%	76%	54.3%	43.0%	78.6%	0.80%	95.7%
Roasting	○	○	●	●	○	●	●	○	○
Winnowing	○	○	○	○	○	○	○	○	○
Grinding	○	●	●	●	●	●	●	○	○
Pressing	○	●	●	●	●	●	●	○	○
Mixing	○	●	●	●	●	●	●	○	●
Tempering	○	●	●	●	●	●	●	○	○
Molding	●	○	○	○	○	○	○	○	○
Packaging	●	○	○	●	○	○	○	○	○
					●		significant impact value		
					○		insignificant impact value		

Note: the significant impact value (symbolized by filled circle (●)) is set at more than 10%. AD: Abiotic Depletion; GW: Global Warming; ODP: Ozone Layer Depletion; AC: Acidification; EU: Eutrophication; CED: Cumulative Energy Demand; FRS: Fossil Resource Scarcity; LU: Land Use; WC: Water Consumption. (Source: Data of this study).

4. Discussion

The CML IA baseline method was used to measure the environmental impact indicators. The obtained results align with those found in the literature. For example, the GW indicator results (1.44 kg CO_2 eq) are comparable to those in Boakye-Yiadom et al. [39] who found 1.65 kg CO_2 eq for extra dark chocolate products, Vesce et al. [31] who found 1.99 kg CO_2 eq, and Perez Neira [45] who found 1.63 kg CO_2 eq on traditional farms. For the dominant use of electrical energy, Borghi et al. [46] found the greatest environmental impact on GW, while the greatest impact was found by Munoz et al. [14] during the mixing, potting, and grinding of the manufacturing phase, and due to fertilizer use in Perez Neira [45]. The energy assessment using CED as an impact indicator on non-renewable fossil and renewable biomass in this study (34.65 MJ/FU) was in line with the results of Recanati et al. [5] at 33.75 MJ/FU, which included non-renewable and renewable energy sources for dark chocolate production in Italy.

Table 5 provides an improvement plan based on the findings in Table 4 that identified the significant process to be improved. The improvement plan is focused on decreasing the environmental footprint without enormous investment costs via collaborations between small-scale chocolate artisan companies and specialty cocoa farmers. In the first stage, small and medium artisanal enterprises are considered the main actors in educating farmers on the use of organic fertilizers made from waste that can be safely used around cocoa farms, such as cocoa pod waste. In the post-harvest stage, the management of fermented pulp waste and the replacement of wooden cocoa bean drying sheet boards with shade nets would be beneficial. In the processing stage, an increase in machine effectiveness and the use of more environmentally friendly paper is recommended. In addition, artisanal chocolate companies need to support farmers by increasing their incomes, providing more environmentally friendly fermentation boxes and dryers, and support converting waste from the cocoa bean production process into materials that can be used to make environmentally friendly organic fertilizers.

Table 5. Scenario Settings for Improvement Plan Process to Reduce Environmental Impacts.

Chain	Description Process	Description of Change	Value Change Calculation
Stage I. Farm Maintenance			
1. Farmer technical assistance program for utilization of biowaste as compost	Cacao pod husk reused as compost	Cocoa pod husk can be used as compost in quantities of up to 300 kg.	- GW from 0.244 kg CO_2 eq to 0.155 kg CO_2 - EU from 0.00144 kg PO4 eq to 0.000114 kg PO4 - AD from 3.4×10^{-6} kg Sb eq to 1.49×10^{-8} kg Sb eq - LU from 18.2 m2a crop eq to 18.5 m2a crop eq
2. Farmer Education Program for the Use of Organic and Environmentally Friendly Fertilizers	Effectiveness of fertilization with the use of organic phosphate fertilizers (horn meal)	SP36 of approximately 4.66 kg replaced with organic phosphate (horn meal)	
Stage II. Post-harvesting			
3. Farmer technical assistance program for Utilization of fermented liquid waste as compost.	Cocoa pulp waste is used to accelerate the composting process	Pulp with a concentration of 250 kg is used as a compost acceleration material	- GW from 0.203 kg CO_2 eq to 0.155 kg CO_2 - EU from 0.0012 kg PO4 eq to 9.5×10^{-5} kg PO4 - AD from 1.98×10^{-6} kg Sb eq to 1.27×10^{-6} kg Sb - ODP from 1.27×10^{-8} kg CFC-11 eq to 8.14×10^{-9} kg CFC-11 - CED renewable biomass (RB) from 15.7 MJ to 9.9 MJ
4. Environmentally friendly cocoa drying-equipment assistance program.	drying board which is entirely made from wood material modified by using shade net	Wooden material for drying 0.174 m^3 of blocks to 0.09 m^3 of logs and modified by replacing the wooden sheets used as a drying base with shade net	
Stage III. Processing			
5. Increase production capacity and improve machine effectiveness.	Effective use of production machinery and refrigerant for cooling	Adding capacity of 10 kg per batch on grinding, mixing and tempering machines as well as adding 20 kg per batch on the cooling process of chocolate bar refrigerant	- AD from 2.19×10^{-6} kg Sb eq to 2.23×10^{-6} kg Sb - GW, from 0.424 kg CO_2 eq to 0.355 kg CO_2 - ODP, from 1.32×10^{-8} kg CFC-11 eq to 6.75×10^{-8} kg CFC-11 - AC from 0.00183 kg SO_2 eq to 0.00153 kg SO_2 - EU, from 0.00223 kg PO4 eq to 0.00187 kg PO4 - FRS from 0.109 kg oil eq to 0.091 kg oil - WC from 0.0994 m^3 to 0.101 m^3 - CED in non-renewable (NRF) fossil from 4.93 MJ to 4.12 MJ.
6. Selecting a more environmentally friendly paper printed packaging.	Selecting the lighter printed paper	Replacing the packaging paper from 4 g to 2 g per package	- AD from 2.21×10^{-6} kg Sb eq to 1.13×10^{-6} kg Sb - AC from 5.15×10^{-4} kg SO_2 eq to 2.62×10^{-4} kg SO_2

(Source: Data of this study).

Figures 5 and 6 show how these changes could alter the environmental impact. The farmer education program on the use of organic fertilizers would reduce the value of the environmental impact indicator for abiotic depletion from organic phosphate from 3.4×10^{-6} to 1.49×10^{-8} kg Sb eq. Conversely, the LU indicator would increase from 18.2 to 18.5 m2a crop eq, thus requiring additional farm maintenance for organic fertilizer. Cocoa pod shell waste, which farmers usually throw away, could be reused as environmentally friendly compost, and can effectively increase fruit weight and nutrients [47]. This change would reduce GW from 0.244 to 0.155 kg CO_2 eq and decrease the environmental impact on the EU indicator from a value of 0.00144 to 0.000114 kg PO4 eq. The average percentage reduction during the first stage is 13.83%.

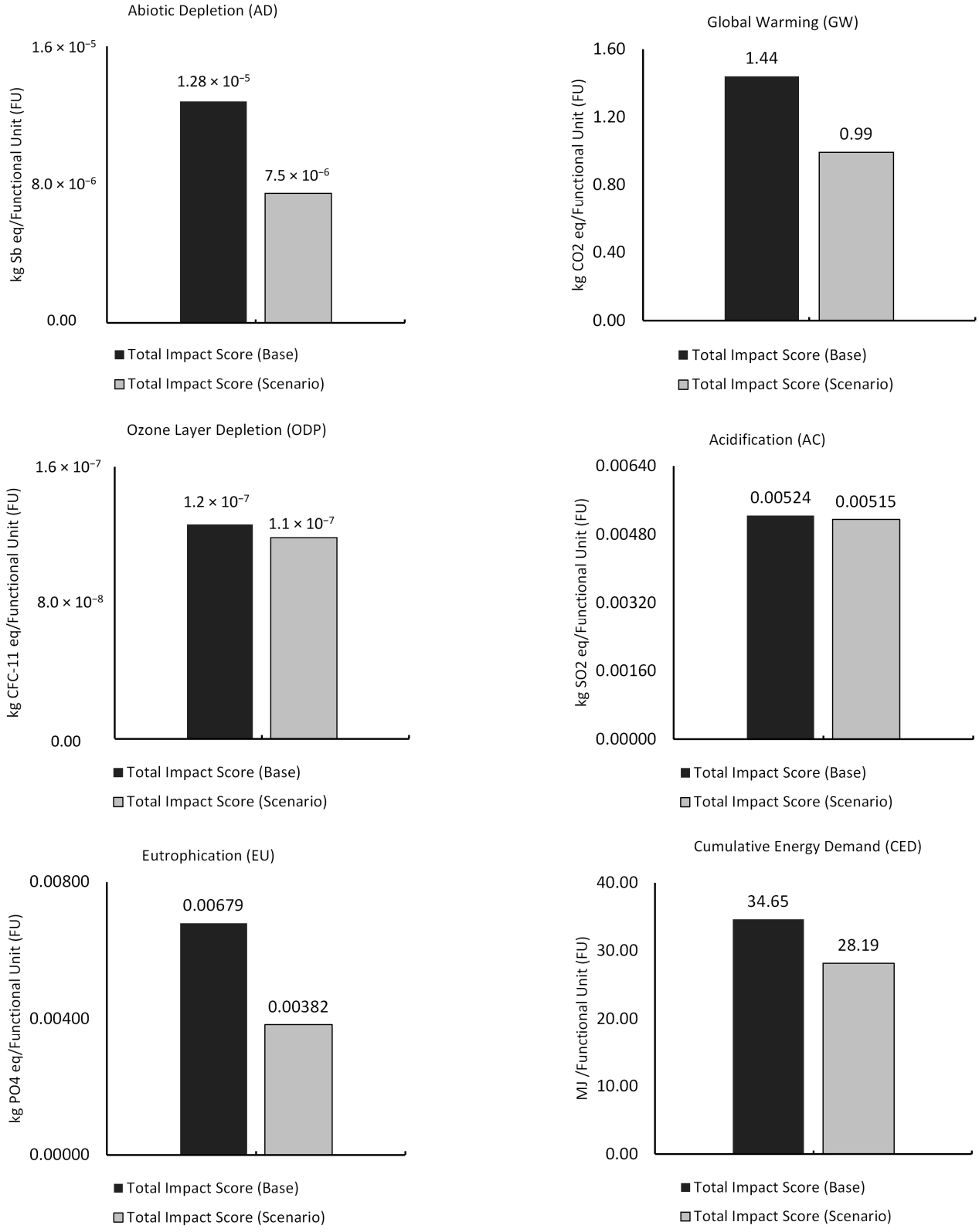


Figure 5. Environmental Indicators Values Changes (for AD, GW, ODP, AC, EU, and CED).

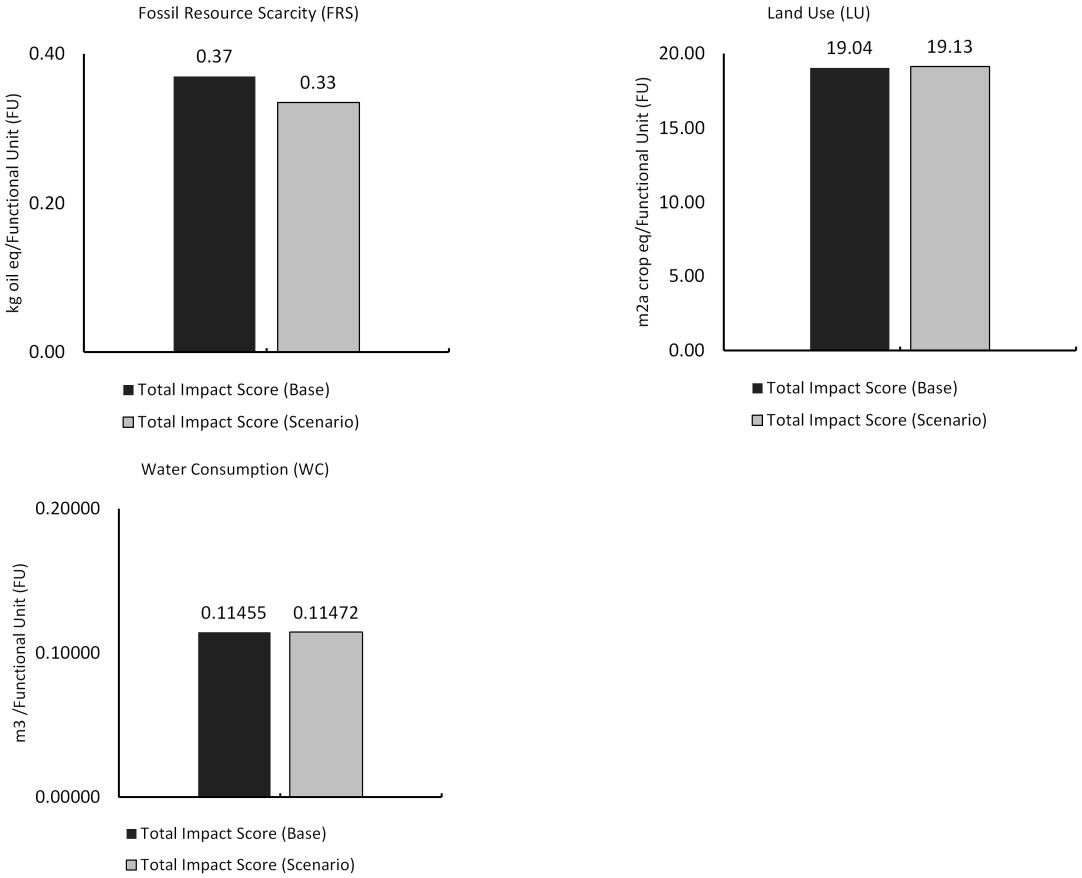


Figure 6. Environmental Indicators Values Changes (for FRS, LU, and WC).

In the second stage (post harvesting), the proposed farmer education program to promote the use of fermented liquid waste as a compost acceleration material would reduce the environmental impact of GW and EU from 0.203 to 0.155 kg CO_2 eq and 0.0012 to 9.5×10^{-5} kg PO4 eq, respectively. The initiative for environmentally friendly cocoa drying equipment involves the replacement of the drying base with a shade net. This would reduce the environmental impact of AD and ODP from 1.98×10^{-6} to 1.27×10^{-6} kg Sb eq and from 1.27×10^{-8} to 8.14×10^{-9} kg CFC-11 eq, respectively. Renewable biomass energy would decrease from 15.7 to 10.1 MJ. The second stage's average percent reduction of environmental impact was 10%.

During the processing stage, the efficiency of the machines could be increased if their capacity and refrigerant capabilities were increased. This would cause GW, AC, EU, and FRS to go from 0.424 to 0.355 kg CO_2 eq, 0.00183 to 0.00153 kg SO_2 eq, 0.00223 to 0.00187 kg PO4 eq, and 0.109 to 0.091 kg oil eq, respectively. For the CED indicator on NRF fuel, the improvement would reduce the impact from 4.93 to 4.12 MJ. Conversely, the ODP indicator goes from 1.32×10^{-8} to 6.75×10^{-8} kg CFC-11 eq and the WC indicator, which had an additional impact due to the use of sugar cane production as a sugar raw material, would go from 0.0994 to 0.101 m^3. The increase in refrigerant capacity failed to contribute to AD, which went 2.19×10^{-6} to 2.23×10^{-6} kg Sb eq. Instead, weight reduction in the dark chocolate packaging decreased AD and AC from 2.21×10^{-6} to 1.13×10^{-6} kg Sb eq and 5.15×10^{-4} to 2.62×10^{-4} kg SO_2 eq, respectively. The average percent reduction in environmental impact during the third stage was 10.2%.

Based on the measurement of the environmental impact at the three stages of the cocoa supply chain, a comparison value is generated between the total baseline value and the total value proposed as a result of the simulation (see Figures 7–9). At the farm maintenance and harvesting stage, impact reduction was carried out by utilizing cacao pod husk biowaste

waste into compost and replacing synthetic fertilizer with organic phosphate, so the impact improvement was obtained with a value of 3.3×10^{-6} kg Sb eq (72.5% of total AD), 0.167 kg CO_2 eq (47.2% of total GW) and 0.00137 kg PO4 eq (80.2% of total EU).

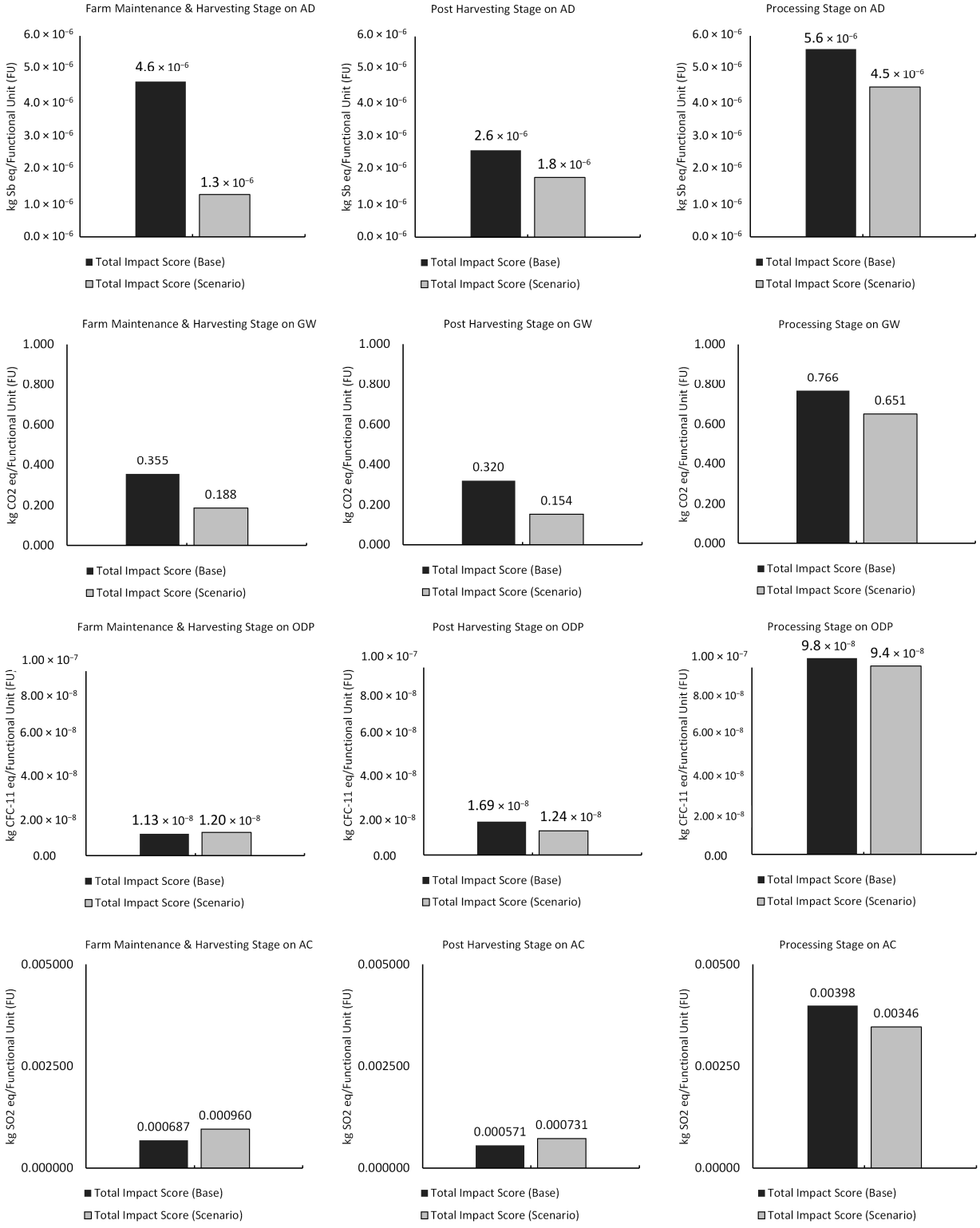


Figure 7. Environmental Indicators Value Changes (for AD, for GW, for ODP, for AC) at each supply chain stage (farm maintenance and harvesting, post-harvesting, and processing).

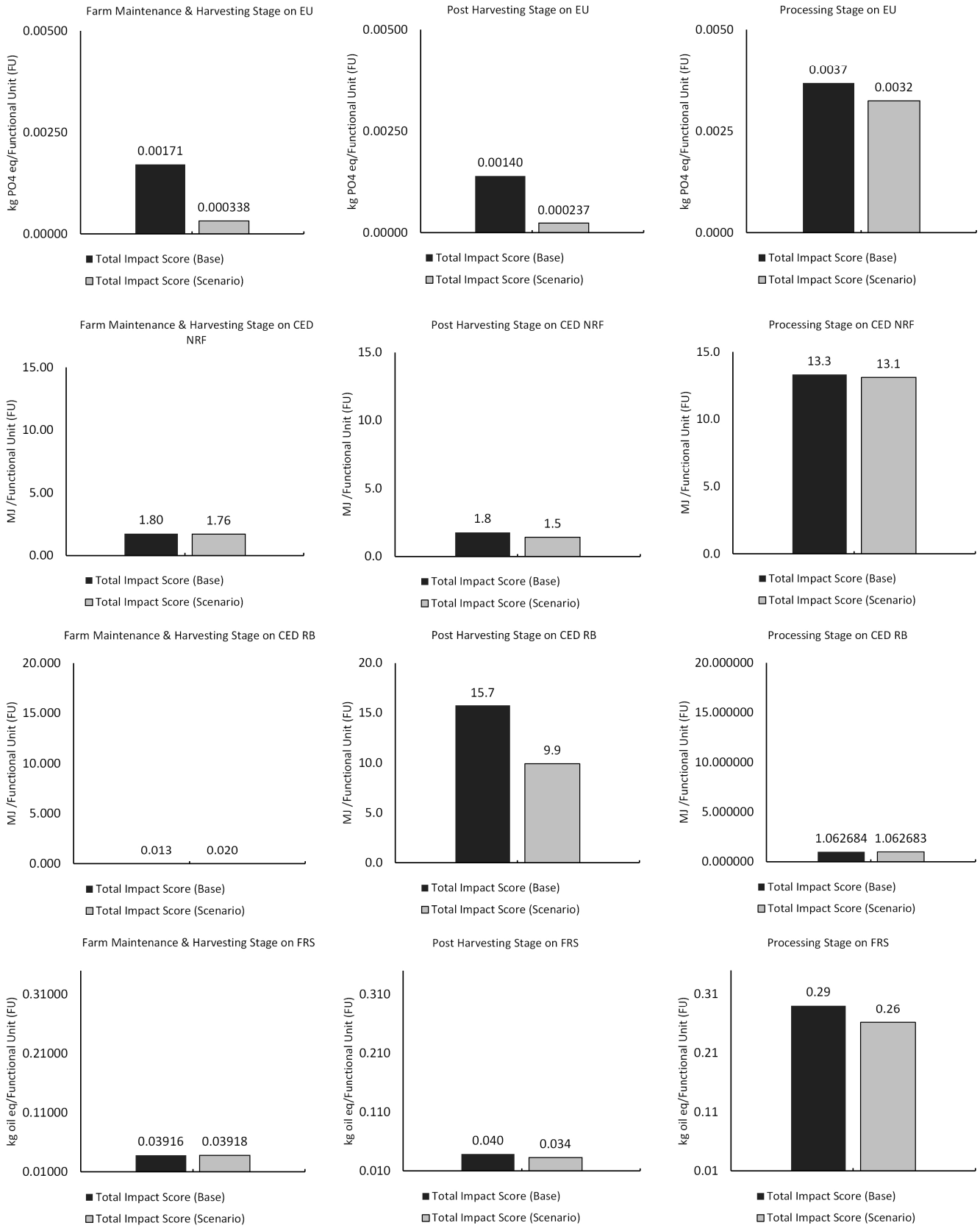


Figure 8. Environmental Indicators Value Changes (for EU, for CED NRF, for CED RB, for FRS) at each supply chain stage (farm maintenance and harvesting, post-harvesting, and processing).

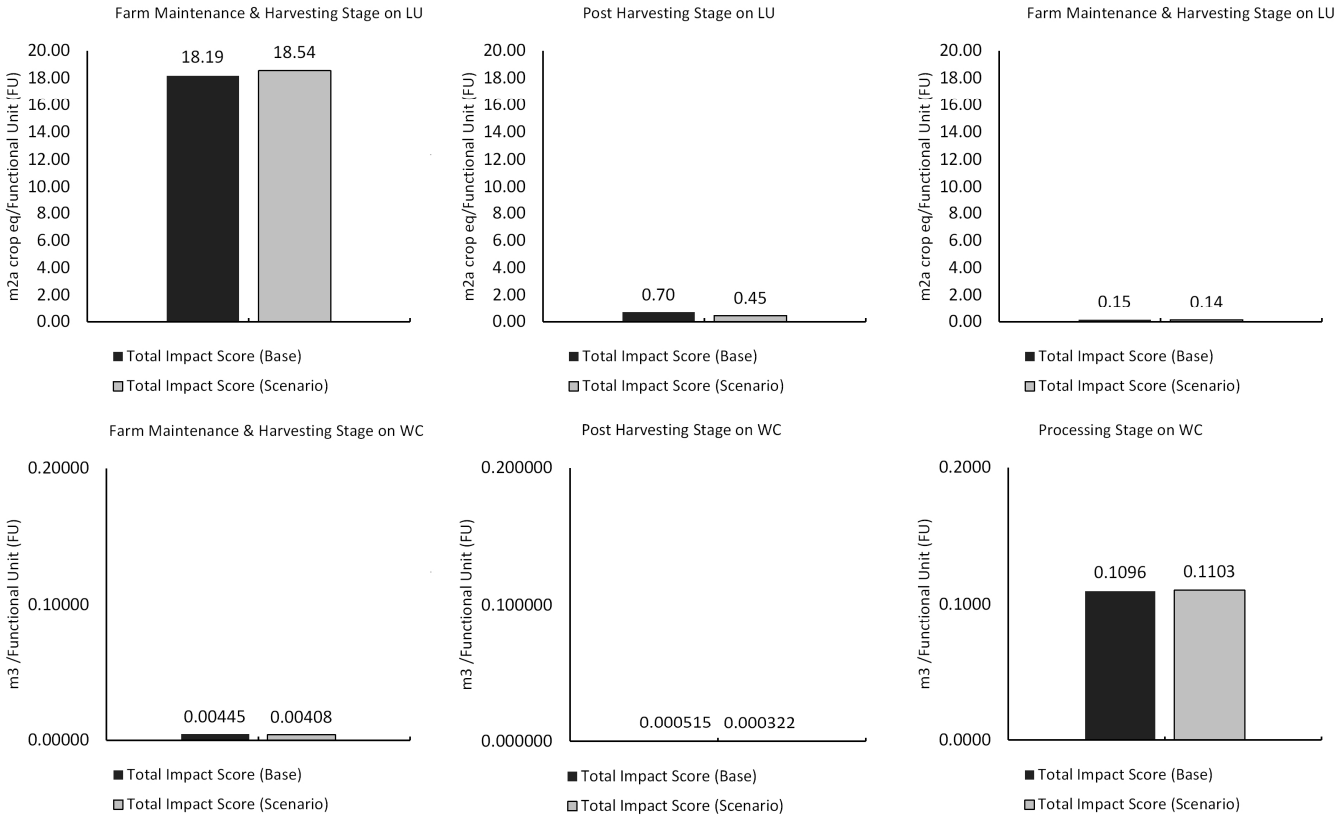


Figure 9. Environmental Indicators Value Changes (for LU, for WC) at each supply chain stage (farm maintenance and harvesting, post-harvesting, and processing).

Furthermore, in the post harvesting stage, efforts to reduce the impact by utilizing biowaste cacao pulp waste as an accelerator for making compost and reducing the percentage of wood-based materials used in cocoa bean drying equipment resulted in an impact improvement with a value of 8.1×10^{-7} kg Sb eq (31.2% of total AD), 0.165 kg CO_2 eq (51.8% of total GW), 0.00116 kg PO4 eq (83% of total EU) and 4.0×10^{-9} kg CFC-11 eq (26.4% of total ODP), 0.366 MJ (20.1% of total CED non-renewable fossil (NRF)) and 5.8 MJ (36.9% of total CED renewable biomass).

In the cocoa manufacturing chain at the processing stage, efforts were made to improve the impact by reducing the weight of packaging material for dark chocolate products and making chocolate production machines more effective. Improving the impact on the effective machine use program resulted in a value of 1.1×10^{-6} kg Sb eq (20.5% of total AD; 0.115 kg CO_2 eq (15% of total GW), 3.8×10^{-9} kg CFC-11 eq (4% of total ODP; 0.00052 kg SO_2 eq (13% of total AC), 0.00043 kg PO4 eq (12% of total EU), 0.03 kg oil eq (10% of total RFS, and 0.2 MJ (2% of total CED NRF).

5. Conclusions

In the simulation results, it is stated that the results showing improvement in the impact indicators at the processing stage are lower than the other two stages, even though in the baseline conditions, the impact contributed by the processing stage is greater in percentage value than the other two stages. The minimum efforts made, such as material replacement, or the effectiveness of machine use, have not been able to provide a large change impact value. In general, the magnitude of the impact on many environmental indicators at the processing stage is due to the dominant use of fossil energy-based energy and fuels. The use of electricity contributes to 29% of total GW, 35% of total AC, 33% of total EU, 11% of total ODP, 30% of total FRS, and 30% of total CED NRF. Meanwhile, LPG

consumption contributes to 11% of total AC, 32% of total FRS, 33% of total CED NRF, and 53% of total ODP.

Improving the environmental impact on the farmer chain, namely the stages of farm maintenance, and post-harvesting can improve the environmental impact with a greater percentage, with lower capital costs and methods more easily accessible to farmers. For example, using cacao pod husk biowaste waste into compost and replacing synthetic fertilizer with organic phosphate can reduce the environmental impact by 75% of total AD, 47.2% of total GW and 80.2% of total EU. Including the post-harvesting stage, where cacao pulp biowaste waste is reused as well as efforts to minimize the use of wood-based materials with impact improvements of up to 75% of total AD, 51.8% of total GW, 83% of total EU, 26.4% of total ODP, 20.1% of total CED NRF and 36.9% of total CED RB. In that way, improving the environmental impact from the farmer's side can increase consumer confidence who are starting to care about environmentally friendly production. This is a special concern to be able to provide solutions to improve the environmental impact caused by manufacturing activities as part of the supply chain for the artisan chocolate industry.

Our findings suggest some development and future trends in the artisan chocolate industry. Buyers are increasingly concerned about the origin of raw materials and the processes practiced in the chocolate processing industry. Consequently, chocolate business is increasingly considering the impact of products, especially on the environment and social aspects. Meanwhile, artisanal chocolate companies are willing to buy raw materials, namely cocoa, at twice the price from farmers who practice environmentally friendly cocoa cultivation. In that way, the artisan chocolate industry is expected to fulfil the sustainability aspects in its supply chain.

The management of the entire supply chain allows small-scale artisan chocolate companies to differentiate their products for environmentally conscious, premium customers. Our use of a LCA encourages the implementation of more focused improvements to reduce environmental impact, boost product value, and compete in the global market. Furthermore, our LCA provided six recommended strategies: (1) utilizing cacao pod husks as compost, (2) replacing phosphate fertilizer (SP36) with organic phosphate, (3) utilizing cocoa pulp waste as compost acceleration material, (4) modifying wood material using a shade net, (5) effective use of production machinery and refrigerant for cooling, and (6) selecting environmentally friendly paper packaging. These six improvement strategies can reduce the environmental impact of the supply chain by approximately 11%.

The elaboration above sheds light on important implications that this research provided in terms of approach and future development of the artisan chocolate industry. First, it provides a systematic LCA procedure that allows the assessment of comprehensive sustainability aspects of specific commodities such as artisan chocolate. As our findings also suggest, the LCA approach in this research captured more focus on the environmental impact of the supply chain. This also leads to the second implication, that is, the six recommended strategies can inspire policymakers or regulators to formulate more environmentally sound rules or protocols that encourage the artisan chocolate industry to achieve a sustainable supply chain.

This research set the stage for the development and employment of the LCA approach, not only in the context of specific commodities such as chocolate artisan but also various commodities by considering all sustainability aspects. In this way, this research has enriched discussion of the LCA literature, especially to the relevant aspects of sustainability. However, current research is still limited to covering only two chains of the life cycle of artisan chocolate, which are cocoa farming and chocolate processing. Therefore, an avenue of future research is to expand the stages to include retailer and consumer chains. Another limitation of this research is that it did not specifically investigate the of cost adjustments regarding the total impacts' reductions. This can be an opportunity for future research to extend and refine our findings. Another avenue of future research is to develop a model that can capture the whole process of the supply chain and generate a prediction for all of the improvement plans proposed in this paper. A continuous modeling approach such as

system dynamics can be an option for this, combined with the LCA approach, in which it results are used as the input for the system dynamics model.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

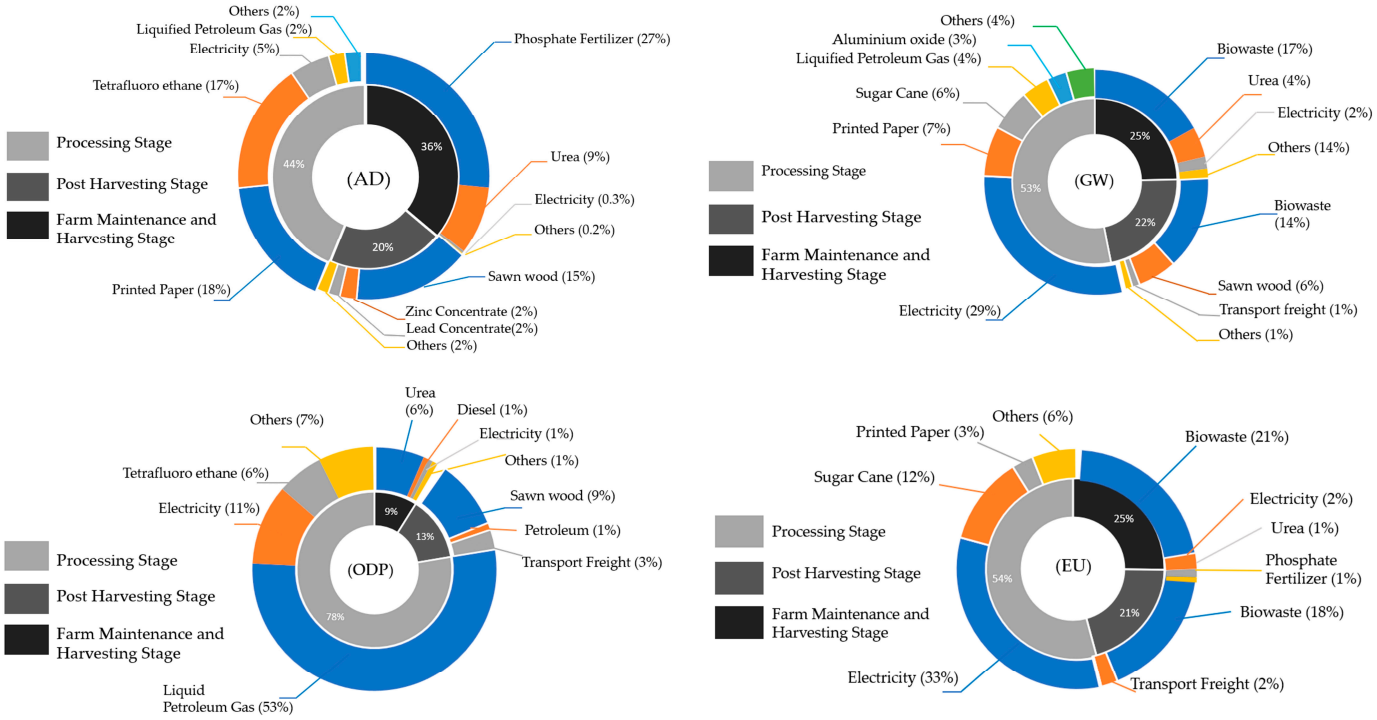


Figure A1. *Cont.*

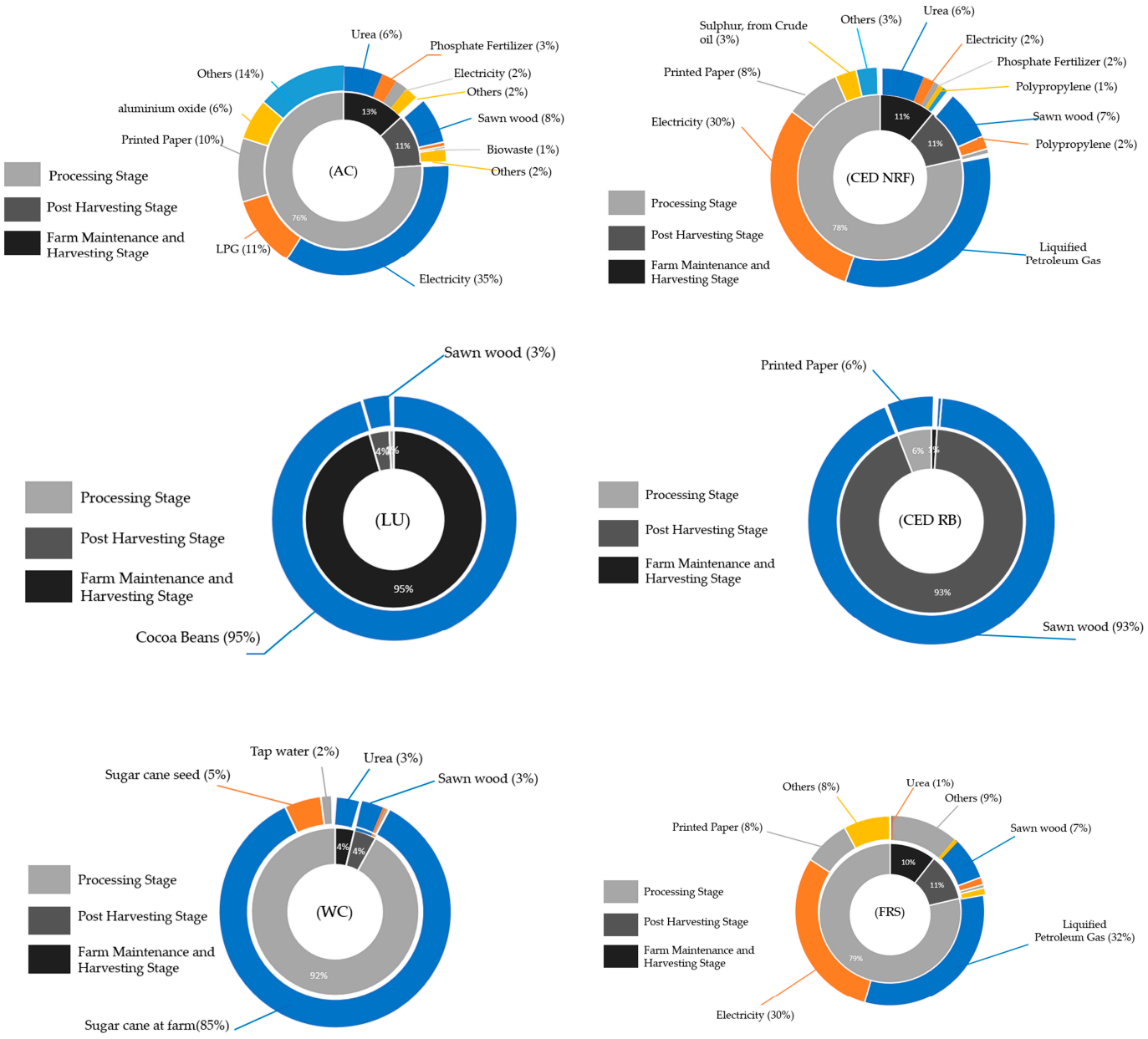


Figure A1. The main process contributing to each impact category.

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